Renewable and Sustainable Energy Reviews 35 (2014) 294–303

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biogas as a sustainable energy source in China: Regional development strategy application and decision making

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ARTICLE INFO

Article history:
Received 18 October 2013
Received in revised form
26 February 2014
Accepted 7 April 2014
Available online 25 April 2014

Keywords:
Biogas energy
Application status
Regional development strategy
Fuzzy analytic hierarchy process
Suitability evaluation

ABSTRACT

Biogas technology has brought benefits to health, the environment, the economy and energy conservation. Vast biomass resources, including organic waste, have the potential for use as feedstock for biogas production in China. This paper presents the development status of biogas application in China. The goal was to provide quantitative information about biogas use, from villages to large cities, to assess the major characteristics of biogas application. Analysis of the opportunities and constraints of the different biogas applications provided the basis for policies for the development of biogas plants and for the adjustment of the scale of biogas development to match local requirements. Based on the characteristics of different biogas plants and geographic regions, a fuzzy analytic hierarchy process model was used to provide a suitability evaluation for development of the regional biogas industry. Results from this model could provide decision support for development strategies for regional distribution plans and the scale of biogas system construction. The findings can also aid further research on balancing energy supply and demand, energy policy formation, and the regional eco-environment development in China.

Contents

1. Introduction

The harmful effects of the use of fossil fuels to the environment, health and society have spurred global interest in the search for cleaner sources of energy. In 2006, about 18% of the global energy consumption came from renewable energy sources, with 13%

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http://dx.doi.org/10.1016/j.rser.2014.04.031
1364-0321/

coming from biomass. China has a long history of using renewable energy sources, including biomass, solar, geothermal, ocean and wind energy [1] and with hydraulic biogas digesters being in use for nearly 100 years. With large biomass resources in China, biogas production potential is significant. By 2007, China had 26.5 million biogas plants, with an output of 10.5 billion m^3. By 2010 output increased to 248 billion m^3 (annually), with 2 billion m^3 produced from domestic waste, 6 billion m^3 from agricultural processing wastes, 150 billion m^3 from animal waste and 90 billion m^3 from crop residues.

Most of the research has focused on the development status of China's biogas industry, and the positive effects of biogas plant construction on the economy, society, ecology and environment [2–5], respectively. However, no research has been published on the systematic evaluation for different biogas applications, which is important to not only understanding the benefits but also to inform construction selection. Moreover, no attempt has been made to discuss regional needs, which takes into account the biogas application characteristics with regional suitability. Thus it is necessary to define the biogas potential at the regional level and conduct economic feasibility evaluations to guide the selection of methods for each region.

The development of sustainable biogas energy relies on the availability of local resources, environmental concerns, and the local societal and economic conditions. However, in China, poor biomass plant distribution has lead to insufficient supply of raw materials, limiting the development of the biogas industry. Appropriate and holistic planning is needed to achieve a favorable cost–benefit ratio to encourage industry stake-holders to make full use of the local natural resources. This planning would also seek to create favorable strategies for biogas industry development. Biogas application is urgently needed in China for systematic industrial development. The key is scientific distribution planning. Hence, a management plan for the biogas industry will provide a clear picture of the whole industry, including biogas plants development, regional differences and the degree of suitability.

This study had three objectives. First to give a holistic description of the present biogas development in China compared to other developed and developing countries. The second is to define why China lags in the application and industrialization of large-scale biogas facilities compared to developed countries. The third objective is to construct a regional suitability evaluation model to provide decision support for development of regional distribution plans, and the scale of biogas system construction.

2. Problem background

For a global review, biogas development and special market characteristics were examined for Europe, USA and Asia.

2.1. International comparisons

The interest in the potential of biogas arose because of the global concerns of energy security and climate change, which pointed to the inevitable end of the wholesale use of fossil fuels. As a result, the mission of the International Energy Agency (IEA) expanded to include extensive cooperation with the major energy consuming and producing countries, such as: China, India, Russia and Organization of Petroleum Exporting Countries (OPEC).

However, a large degree of geographical variability in biogas utilization and development was found between developed and developing countries. The biogas development conditions in representative developed and developing countries are shown in Fig. 1, which shows that biogas development in developed countries has a better, more extensive infrastructure, a mature industrial system, and a more highly educated labor force than in developing countries [6,7].

In developed countries, the biogas development characteristics are as follows: (i) importance is attached to developing the recovery and utilization of landfill gas (LFG). LFG represents around 85.5% and 75% of all biogas output in Britain and the

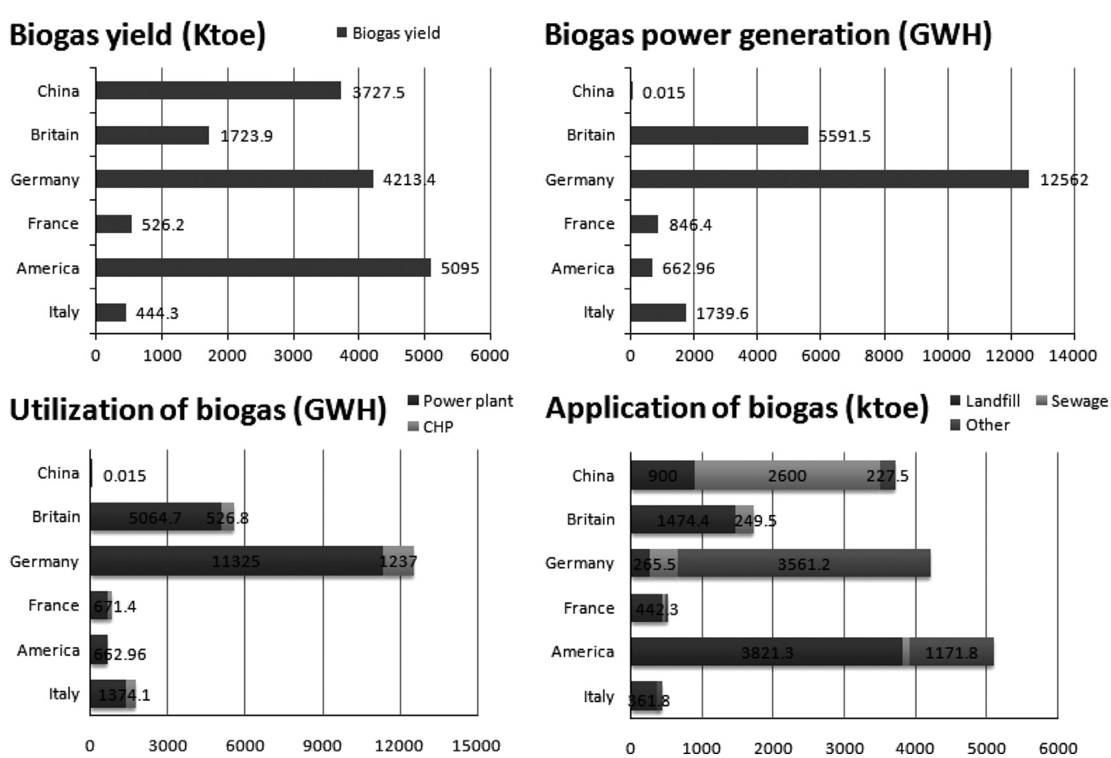

Fig. 1. Biogas development in developed and developing countries.

United States respectively [8]. (ii) Biogas energy use efficiency is high. Biogas is mainly used to generate electricity and for combined heat and power generation (CHP). Refined biogas, which is already widely used in developed countries such as Sweden, France, Switzerland and Denmark [9], is used as fuel for cars or enter the urban fuel network. (iii)The degree of concentration and industrialization is high. Most digester projects are located on dairy farms, which are most often concentrated in areas where many large companies operate. For example: Strabag Umwe ltanlagen GmbH (Germany), Axpo Kompogas AG (Switzerland), Biotechnische Abfallverwertung (Germany), Organic Waste Systems (Belgium) [10].

Most developing countries are now centers for labor-intensive mass production industries, have large rural populations engaged in agriculture, and a strong correlation between low incomes and high population growth. Because of the energy demand in the rural areas, biogas energy plays an important role and is a suitable tool for making the maximum use of scarce resources, especially for farmers in developing countries, who are in great need of fertilizer for maintaining cropland productivity [11] but are unable to afford the high investment costs for the construction of medium or large scale plants [12,13]. Effective and widespread implementation of domestic biogas technology has occurred in developing countries [14], such as India, China and Nepal [15], but these often only provide a few households with gas for cooking and lighting.

The industrial development of the biogas still has a long way to go as the irregular supply of biogas feedstock, the narrow market need, the uneven production, and costly biogas utilization have led to a lack of competitiveness in the current market. Thus, it is essential for developing countries to build an efficient biogas industry system while at the same time considering the local geographic and economic conditions.

2.2. Chinese situation

As the world's fastest developing country, China has a unique biogas model which is different from both typical developing and developed countries. Since 2002, China has been the world's second largest energy user and is facing the two severe challenges of energy shortages and an increased need for environmental protection [1].

Biogas production from anaerobic digesters has been widely used in China for 50 years and over those years, the biogas engineering systems have significantly improved [11], and have now reached an advanced level of equipment design, fermentation technology and engineering construction. At present, China is the world's largest family-scale biogas producer [16]. Since 2003, the Chinese central government has invested 31.5 billion RMB in biogas engineering construction, from which more than 150 million people benefit.

However, on the whole, there is still a large gap when compared to developed countries, particularly when taking account of resource utilization, reasonable price structures, a comprehensive market and a timely service system. Above all, the barriers to biogas development in China are twofold; economic efficiency because of the current low industrial and technological level and regional differences [17].

Regional geographic characteristics and the differing social-economic levels have resulted in uneven development of the eastern,

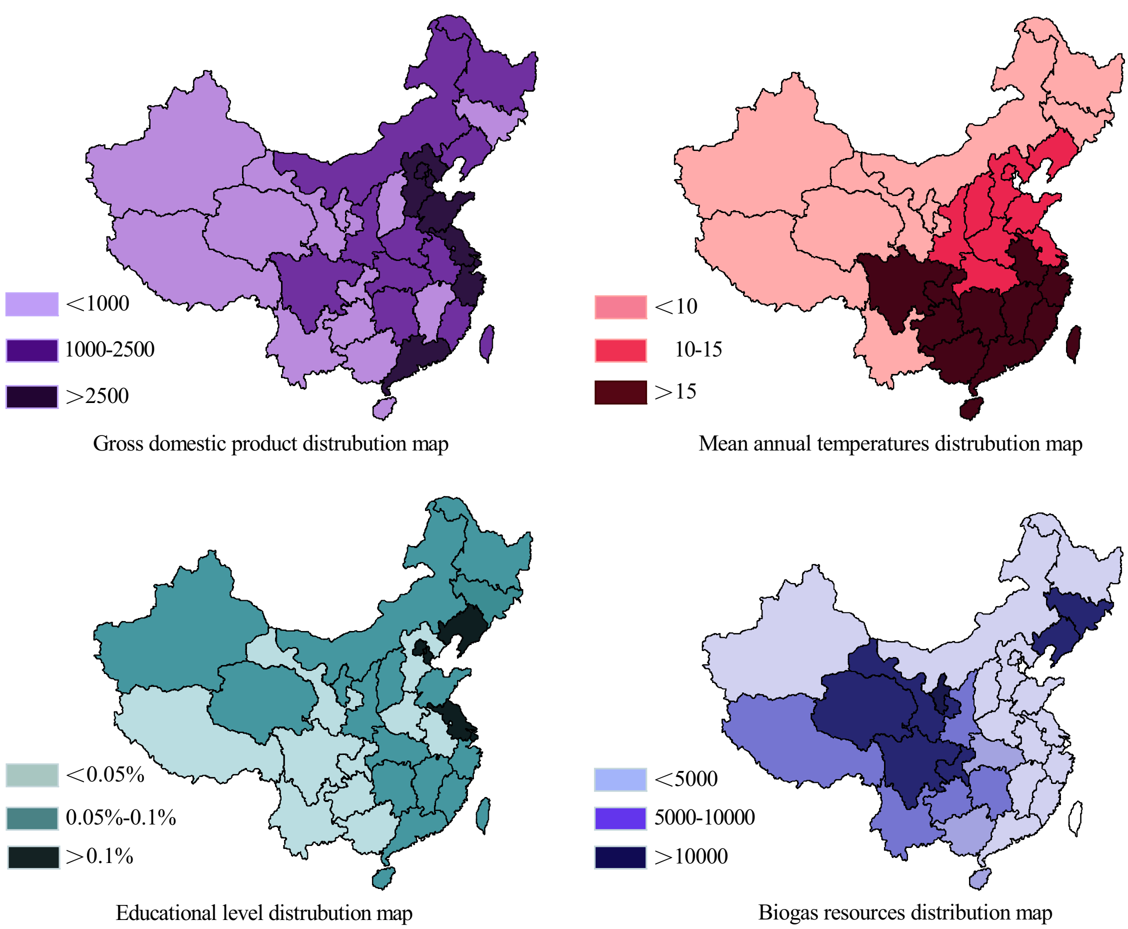

Fig. 2. Related distributions of biogas in China.

central and western regions in China. The distributions of biogas in China are shown in Fig. 2. In 2007, 60% of China's population or 0.9 billion people lived in rural areas. Since the adoption of economic reform and the open-door policy in 1978, rural areas have experienced unprecedented economic development. However, regional rural inequality remains at a high-level and the coastal/interior income differential continues to increase [18].

Biogas resources in China are widely distributed but extremely uneven. In 2007, 1,198,910 were skilled biogas workers, and of these, 197,656 were certificated. Although the education level of rural children is improving, educated people in rural areas are more likely to migrate to the cities to earn higher wages, leaving a rural population with a relatively low educational level and poor professional and technical qualifications [19]. This has created a situation where skilled manpower is available, but not in the regions where it is most needed [20].

The temperature in China varies greatly between the north and south due to the large latitude range and the complex topography. Most of the biogas digesters operate in a mesophilic range of 30–35 °C, but it is possible to operate these digesters in a thermophilic range with higher operating costs, lower processing stability, and increased structural requirements [21]. In the northern regions, which have extremely cold winters, the operating temperature for the promotion of biogas is restricted, especially for family-scale biogas projects in rural areas.

3. The status of biogas applications in China

Biogas is produced from different organic materials and in different environments using micro-organisms operating in anaerobic conditions. Three main biogas applications are used in China: (i) family scale biogas plant (FP), (ii) municipal waste water treatment plant (MP), (iii) large scale biogas plant (LP) [22].

3.1. Family scale biogas plant

In 2007, 60% of China's population or 0.9 billion people lived in rural areas. It is estimated that 35 million family scale biogas plants were operating in China, which is the highest number in the world [16]. These plants produced 12 billion m^3 of biogas, with plant numbers reaching 41 million by the end of 2011. This program has great potential, especially as since 2010 domestic energy demand in rural areas has grown quickly.

By the 21st century, the Chinese government had begun to focus on supporting rural biogas projects, which has involved the provision of subsidies, planning, design, construction, operation and maintenance. Between 2001 and 2005, 3.4 billion RMB from the central government funds was allocated to assist 3.75 million households [23]. Combined provincial and local government subsidies for family scale biogas plants averaged 322 RMB per household in 2008, but these varied widely [24]. However, 26.5 million biogas digesters were in China's rural areas in 2007, only 60% of which were operating normally [25,26]. Such trends reflect an emphasis on plant construction rather than operation, maintenance or repair [25].

In northern regions of China, the biogas production rate is low during winter, a period of the year when the farmers have a greater need for energy. These digesters have small-scale biogas engines and lack controls and heating technologies to allow for an adjustment in the operating temperature to complete co-digestion of different feedstock. The lack of control leads to a low production efficiency and limited application [26].

3.2. Municipal waste water treatment plant

Water shortages and the drive to recycle have increased interest in the reuse of reclaimed waste water [27]. Untreated municipal waste water (MWW) with poor disinfection can not only cause severe ecological harm but also public health problems through the microbial contamination of groundwater [28].

However, MWW contains a large number of micro-organisms, organic matter, nitrogen, phosphorus and potassium, all of which are valuable resources [29]. MWW emissions were 37.121 billion m^3 in 2009, equal to about 5.94 million tons of dry sludge. A 2009 survey of 1850 domestic sludge purification biogas plants in China, found that the total biogas yield was 0.2 million m^3. Since a huge amount of sludge is produced in China, sludge anaerobic digestion could be used more widely. Anaerobic digestion of MWW was limited due to high operating costs and poor technical support. Secondly, only 25% of MPs have sludge treatment plants in China [30].

3.3. Large-sized biogas plant

LP construction began in 1998 and since that time has had rapid development. By the end of 2009, 25,012 large biogas projects were operating in China, with a total biogas capacity of 7.255 million m^3, and an average daily biogas production of more than 794.7 m^3 for each project, LPs converted biogas to a variety of energy forms including heat (via burning), steam and electricity [30].

Three main LP construction models are used in China: the industrial organic sewage biogas project (IOSP), the large scale livestock farm biogas project (ILFP) and the landfill gas biogas project (LFGP). This LP development status is as shown in Table 1.

New hybrid materials such as straw and kitchen wastes are gradually being promoted for the ILFP, and advanced anaerobic reactors are being widely used, such as the up flow anaerobic sludge blanket (UASB) and the internal circulation (IC), with an IOSP of 50% and 15% respectively [30].

Unfortunately, the LP products of biogas, organic fertilizer, and electricity lack competitiveness and cannot reliably or efficiently enter the market, reducing the economic benefits [31]. What's more, a large volume of biogas slurry and residue lack the appropriate treatment, which then become waste leading to secondary pollution [32]. On top of these issues, the decentralized land management and dense population in China make it difficult to recycle slurry and residue from large projects.

In recent years, in the use and scale of biogas plants China has become significantly larger, more standard and more modern. Thus,

Table 1
LP development status in China.

Project category	Unit	Quantity of project
(i) Quantity of LP resources	1.0×10^8 m^3	
Industrial organic sewage biogas project		280.83
Large scale livestock farm biogas project		66.46
Landfill gas biogas project		88.96
Total		436.25
(ii) Quantity of LP project	n	
Industrial organic sewage biogas project		2000
Large scale livestock farm biogas project		22,570
Landfill gas biogas project		442
Total		25,012
(iii) Biogas yield of LP project	1.0×10^8 m^3	
Industrial organic sewage biogas project		50.07
Large scale livestock farm biogas project		4.55
Landfill gas biogas project		18
Total		72.55

rational distribution and reasonable performance are becoming more important in the development of the biogas industry.

4. Decision support for regional development strategy

4.1. Methodology

Generally, a biogas system is a complicated engineering project that involves many factors. These factors include raw materials selection, methane fermentation technology, equipment and technology for biogas facilities, comprehensive utilization of solid and liquid residues. Therefore, a systematic analytical method is needed.

Furthermore, biogas projects involve considering relevant technical, economic, environmental, and social factors that may be delineated by either quantitative or qualitative ways or both. This complexity challenges the decision making arena. Decision makers need a more credible approach to reach a sustainable solution that involves quantitative and qualitative considerations.

Traditional industrial project evaluation methods focus too heavily on the financial viability of a project and consequently are unable to measure regional suitability effectively. These mathematical models, which rely only upon a quantitative interpretation, lack a qualitative interpretation of the social and political factors. Within this context, several sources of uncertainties should be addressed which can affect the choice of the optimize biogas project solution.

The suitability evaluation could be conducted by using the fuzzy analytic hierarchy process (AHP), which allows for a simultaneous evaluation [33,34] based on the characteristics of the region and the biogas plants. Many fuzzy-AHP methods have been proposed for energy policy and development plan analysis, such as the renewable energy dissemination [35], technology assessment [36], solid waste systems [37] and power generation project management [38]. The proposed fuzzy-AHP approach used for the suitability evaluation can be expressed as following steps.

Step 1: Establishment of the index system and hierarchy model construction. The factors and sub-factors are used to set up the index system. The AHP hierarchy model is then structured based on the index system.

Step 2: Factor and sub-factor weight calculation. The local weights of the factors and sub-factors are calculated using pairwise comparison matrices. Pair wise comparison judgments are made using triangular fuzzy scales regarding relative importance to measure the local weights. Then the sub-factor global weight is calculated by multiplying the sub-factor local weight with the factor local weight to which it belongs. The development of biogas systems is limited by many regional factors, but these limits are not valid for every sub-factor system and may differ depending on the structure and objectives of the sub-factor system. Fuzzy scales for importance are given in Table 2.

Fuzzy AHP has been applied to the triangular membership functions and Chang introduced a new extent analysis method [39] and the principle of triangular fuzzy number (TFN), which was applied to prioritize the importance of factors from pair-wise comparisons in this research. Modeling using TFN has proven to be an effective way for formulating decision problems where available information is subjective and imprecise [40]. TFN is expressed with boundaries instead of crisp number, it is defined as $\tilde{M}=(l,m,u)$. The membership function $\tilde{M}(x)$: $R\rightarrow[0, 1]$ of the TFN $\tilde{M}=(l,m,u)$ defined on R is given by

$$\tilde{M}(x)=(x)=\begin{cases}\frac{x}{m-l}-\frac{l}{m-l}, & x\in[l,m]\\ \frac{x}{m-u}-\frac{u}{m-u}, & x\in[m,u]\\ 0 & \text{otherwise}\end{cases} \tag{1}$$

where $l\le m\le u$, and m is the median and most possible value of fuzzy number $\tilde{M}$, l and u is the lower and upper bounds of $\tilde{M}$ respectively. Consider two TFNs $\tilde{M}_1=(l_1,m_1,u_1)$ and $\tilde{M}_2=(l_2,m_2,u_2)$, ($l_1$ and $l_2\ge 0$). The operation laws are as follows:

$$(l_1,m_1,u_1)\oplus(l_2,m_2,u_2)=(l_1+l_2,m_1+m_2,u_1+u_2) \tag{2}$$

$$(l_1,m_1,u_1)\otimes(l_2,m_2,u_2)\approx(l_1\times l_2,m_1\times m_2,u_1\times u_2) \tag{3}$$

$$(l_1,m_1,u_1)^{-1}\approx(1/u_1,1/m_1,1/l_1) \tag{4}$$

The value of the fuzzy synthetic extent of the ith object is defined as

$$S_i\approx\sum_{j=1}^{m}\tilde{M}_{ij}\otimes\left[\sum_{i=1}^{n}\sum_{j=1}^{m}\tilde{M}_{ij}\right]^{-1} \tag{5}$$

$$\sum_{j=1}^{m}\tilde{M}_{ij}=\left(\sum_{j=1}^{m}l_{ij},\sum_{j=1}^{m}m_{ij},\sum_{j=1}^{m}u_{ij}\right) \tag{6}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\tilde{M}_{ij}=\left(\sum_{i=1}^{n}l_{ij},\sum_{i=1}^{n}m_{ij},\sum_{i=1}^{n}u_{ij}\right) \tag{7}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m}\tilde{M}_{ij}\right]^{-1}\approx\left(1/\sum_{i=1}^{n}u_{ij},1/\sum_{i=1}^{n}m_{ij},1/\sum_{i=1}^{n}l_{ij}\right) \tag{8}$$

The TFN value of $S_i=(l_i, m_i, u_i)$ is calculated using Eqs. (5)–(8). Then the values of S_i are compared and the degree of possibility of $S_j=(l_j, m_j, u_j)\ge S_i=(l_i, m_i, u_i)$ is calculated, it can be equivalently expressed as follows:

$$V(S_j\ge S_i)=\text{height}(S_i\cap S_j)=u_{S_j}(d)$$
$$=\begin{cases}1 & \text{if } m_j\ge m_i\\ 0 & \text{if } l_i\ge u_j\\ \frac{l_i-u_j}{(m_j-u_i)-(m_i-l_i)} & \text{otherwise}\end{cases} \tag{9}$$

To compare S_i and S_j, we need both the values of $V(S_j\ge S_i)$ and $V(S_i\ge S_j)$. The minimum degree possibility $d(i)$ of $V(S_j\ge S_i)$ ($i, j=1, 2, \ldots, k$) can be defined by

$$\begin{aligned}V(S\ge S_1,S_2,\ldots,S_k)&=V[(S\ge S_1)\text{ and }(S\ge S_2)\text{ and}\ldots(S\ge S_k)]\\&=\min_{i=1,2,3,\ldots,k}V(S\ge S_i)\end{aligned} \tag{10}$$

The local weight vector is then normalized as follows:

$$W=(\min V(S_1\ge S_k),\ \min V(S_2\ge S_k),\ldots,\ \min V(S_3\ge S_k))^{\mathrm{T}} \tag{11}$$

where $k=1, 2, \ldots, n$ and W is a non-fuzzy number.

Step 3: Regional development suitability evaluation. The regional suitability degree (RSD) value is calculated as the sum of the sub-factor evaluation values. The sub-factor condition value is a product of its global weight and the corresponding fuzzy linguistic value (FLV). Fuzzy linguistic scalars are used to measure the sub-factors FLVs. The linguistic scalars and corresponding fuzzy values are defined as: Very good = 1, Good = 0.75, Medium = 0.5, Poor = 0.25, Very poor = 0.

As RSD is the sum of all sub-factor condition weights, biogas industry suitability evaluation of the region and decisions could be

Table 2
Fuzzy scale for importance.

Linguistic scale for importance	Fuzzy scale	Reciprocal scale
Equal importance	(1, 1, 1)	(1, 1, 1)
Moderate importance	(1/2, 1, 3/2)	(2/3, 1, 2)
Strong importance	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strong importance	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)
Extreme importance	(7/2, 4, 9/2)	(2/9, 1/4, 2/7)

made by comparing the RSD to the corresponding suitability threshold (T_{FP}, T_{MP}, T_{LP}) determined according to certain FLVs with judgments of the expert team. To determine the T_{FP}, set the fuzzy linguistic scales of C_2 sub-factors at Medium, the C_3 sub-factors at Good, and use the values of $P=4000$ (1000 head) and $Q=1000$ (1000 tons) to determined the FLVs of C_1 sub-factors. To determine the T_{MP}, set fuzzy linguistic scales of the C_2 sub-factors and C_3 sub-factors at Good, use the values of $B=400$ (100 million tons) determined the FLVs of C_1 sub-factors. To determine the T_{LP}, set fuzzy linguistic scales of the C_2 sub-factors at Good, and the C_3 sub-factors at Medium, and use the values of $P=4000$ (1000 head) and $Q=1000$ (1000 tons) determined the FLVs of C_1 sub-factors. Therefore, the T_{FP}, T_{MP}, T_{LP} were determined as 0.5821, 0.5556, 0.5972, respectively. For RSD $\geq$ T, the region was considered to be suitable for the corresponding biogas plant. For $RSD < T$, the region was considered to be unsuitable for the corresponding biogas plant.

4.2. Application example

To illustrate the decision support process of a regional development strategy, an example is shown to apply the proposed suitability evaluation to the regional development of biogas plants. Sichuan and Shandong were chosen as the representative regions, for the two provinces have all the major biogas applications without specific regional development strategies.

Shandong Province is a coastal province located in eastern China with a total land area of 157,100 km^2. The gross domestic product (GDP) was 3107.21 billion RMB in 2008, accounting for 10.33% of total GDP of China, ranking the second in the nation [41]. The provincial government plans to establish a special 1.2 billion RMB foundation to support the development of renewable energy by interest payments on loans, subsidies, incentives and tax rebates [42]. Sichuan is a province in the central-western China. It is bordered by the Tibetan Plateau in the west and by the Three Gorges and the Yangtze River in the east. Household biogas digesters are especially prevalent in the Yangtze River Basin, with Sichuan Province having the largest number of biogas plants, at 2.94 million [14]. The basic information which FAHP model of Shandong and Sichuan province were shown in Table 3.

Sixteen experts from academic, research and industrial sectors were selected to establish the index system and perform the fuzzy judgments. Their consensus answers were aggregated using a geometric mean and then input into the fuzzy evaluation matrix.

The geometric mean was the aggregation procedure used to measure the individual consistency of judgment matrices in the 16 experts' group decision making especially when they have an acceptable inconsistency. With A_k as the judgment matrix provided by the kth experts, where $A_r=[a_{ijr}](r=1,2,\dots,k)$ the matrix A calculated by geometric means was

$$a_{ij}=\sqrt[k]{\prod_{r=1}^{k} a_{ijr}} \tag{12}$$

$$a_{ij}^2=\frac{1}{k}\sum_{r=1}^{k}(a_{ijr}-a_{ij})^2 \tag{13}$$

where $i,j=1,2,\dots,N$

The judgment matrices for resources used the animals' data base for the energy potential estimation (ABEPE) model [43]. The amount DS_{ij} in tonnes of dry solids produced by animal (plant)

Table 3
Basic data of Shandong and Sichuan province in 2011.

AHP factor	Historical data index	Unit	Shandong	Sichuan
Resources situation	Gross output value[a]	100 million yuan	7409.75	4081.81
	Output of grain	10,000 tons	4426.3	–
	Output of cotton	10,000 tons	78.5	1.42
	Output of oil bearing crops	10,000 tons	341	268.5
	Stocked pigs	10,000 heads	2837.13	5132.4
	Stocked cattle	10,000 heads	492.86	940.2
	Stocked sheep	10,000 heads	2150.90	1671.9
	Municipal waste water	100 million tons	22.8	19.9
	Industrial organic sewage	100 million tons	20.8	8
Socioeconomic factors	Population at year-end	10,000 persons	9591	9001.3
	Biogas investment[b]	10,000 RMB		
	FP		14,657	18,347
	MP		97,400	7728
	LP			
	Urban population	10,000 persons	3945	2355.2
	Rural population	10,000 persons	5646	6646.1
	Employment	10,000 persons	6485.6	4715
	Higher education schools		136	99
	Higher education enrollment		165.8	122.3
	Annual per capita income	RMB	19,946	17,899
Environmental condition	Sunshine hours[c]	h		
	Spring		680.1	262.5
	Summer		521.9	278.3
	Autumn		516.0	146.4
	Winter		428.0	93.4
	Annual total solar radiation	MJ/m^2	4989	3829
	Average temperature[c]			
	Spring		16	17
	Summer		27	24
	Autumn		15	16
	Winter		−1	6

[a] Gross output value of agriculture, forestry, animal husbandry and fishery.
[b] Including central government investment, local government investment, famers (or construction unit) self-financing.
[c] Provincial capital.

Table 4
The judgment matrices of C_2 and C_3 factors.

Sub-factor	Units	Range				
		Very poor (0)	Poor (0.25)	Medium (0.5)	Good (0.75)	Very good (1)
C_{21}	RMB	< 14,000	14,000–15,000	15,000–16,000	16,000–17,000	> 18,000
C_{22}	RMB	< 16,000	16,000–17,000	17,000–18,000	18,000–19,000	> 19,000
C_{23}	%	< 1.3	1.3–1.5	1.5–1.7	1.7–1.8	> 1.8
C_{31}	°C	12–13	13–14	14–15	15–16	> 16
C_{32}	h	< 100	100–300	300–500	500–700	> 700
C_{33}	MJ/m^2	< 2000	2000–3000	3000–4000	4000–5000	> 5000
C_{34}	–					

Table 5
Regional suitability evaluation index system.

Factor	Sub-factor
Resources situation	Amount of biogas raw material Raw material organic content Resources processing technology Biogas residue/slurry treatment
Socioeconomic factor	National subsidies/investment Annual per capita income The educated population rate
Environmental condition	1.6 m average ground temperature Annual sunshine hours Annual total solar radiation Geographical location condition

grouping i in region j was calculated by the following formula:

$$DS_{ij} = B_{ij}(P_{ij} + Q_{ij}) \tag{14}$$

where P_{ij}, in animal heads counted in region j, was the population of animal grouping i, Q_{ij} was the crop tons counted in region j, and B_{ij} is the dry solids byproduct factor of animal (crop) i in region j in terms of tonnes per heads (tons). For the MP, P_j was the sewage counted in region j. The total amount of dry solids DS_{ij} in tones estimated in region j was given by

$$DS_{ij} = \sum_{a} DS_{ij} \tag{15}$$

The judgment matrices of C_2 and C_3 factors were shown in Table 4.

To establish the index system for the regional suitability evaluation, the index system described in Section 2.2 was chosen. Temperature, a necessary condition for biogas fermentation, the availability of resources, and the socioeconomic condition, both of which influence the construction and maintenance of biogas plants, are key factors for successful regional biogas development. Thus, three main factors were considered: resource availability, socioeconomics, and the environmental condition. The index system was formed as in Table 5.

Fig. 3 shows the AHP hierarchy model structure based on the index system. On the top level is the goal. The three key factors are on the second level and the corresponding sub-factors are on the third level. On the fourth level, the RSD is computed.

An enhanced state diagnostic approach based on the fuzzy AHP method using triangular fuzzy numbers (TFN) was applied to prioritize the relative importance of the factors and sub-factors from the pair-wise comparisons. Table 3 shows the pair-wise comparison matrix for the three factors developed by the expert team using triangular fuzzy scale judgments. The mean values for each column were identified as shown in Table 4, the results of which are shown in Table 6.

All pair-wise comparison matrices were formed in the same manner. The local weights were calculated using Chang's method [39]. The fuzzy synthetic extent TFN values for the three factors were calculated using the mean values presented in Table 7, so that

$$S_1(C_1) = (2.548,\ 3.047,\ 3.665) \otimes (1/10.762,\ 1/8.921,\ 1/7.516) \approx (0.237,\ 0.342,\ 0.488),$$
$$S_2(C_2) = (2.482, 2.925, 3.544) \otimes (1/10.762,\ 1/8.921,\ 1/7.516) \approx (0.231,\ 0.328,\ 0.472),$$
$$S_3(C_3) = (2.486,\ 2.949,\ 3.553) \otimes (1/10.762,\ 1/8.921,\ 1/7.516) \approx (0.231,\ 0.331,\ 0.473).$$

Then the values for the fuzzy synthetic extent S_i were compared individually and the values obtain for $V(S_i \geq S_j)$: $V(S_1 \geq S_2) = 1.000$, $V(S_1 \geq S_3) = 1.000$, $V(S_2 \geq S_1) = 0.944$, $V(S_2 \geq S_3) = 0.988$, $V(S_3 \geq S_1) = 0.955$, $V(S_3 \geq S_2) = 1.000$. The minimum possibility degree of $V(S_j \geq S_i)$ was obtained. Thus, the factors weight vector was determined and normalized as $W_{factors} = (0.345, 0.326, 0.329)^T$, namely the weights of C_1, C_2 and C_3 were determined as 0.345, 0.326 and 0.329, respectively. The sub-factors local weights were calculated in a similar way. A global sub-factor weight was then computed by multiplying the sub-factor local weight with the factor local weight to which it belongs. All the obtained weights are shown in Table 8.

The FLV were then determined by the expert team using the aforementioned fuzzy linguistic scalars according to the corresponding sub-factor's condition in Sichuan and Shandong, respectively. The sub-factor evaluated value was calculated as a product of the sub-factor global weight and the corresponding FLV. The RSD was calculated as the sum of all the sub-factor evaluated values. All the computed FLVs and evaluated values of the sub-factors as well as the RSDs are listed in Table 9.

Consistency check was validated by using the approach described in [44] that the propose evaluation gives consistent results. According to the evaluation results, the regional development suitability for each kind of biogas application was obtained. To compare the RSDs with corresponding T, FP was identified as the optimum choice for Sichuan and LP seem to be the optimum choice for Shandong, with the significant difference due to the varying biogas resources and socioeconomic situation between the two regions. The evaluation results were consistent with the actual situation. It demonstrates that effective decision support for the regional development strategy of biogas applications can provide suitability evaluation. For different regions the biogas investment structure needs to be optimized. According to the results, in Sichuan and Shandong, for instance, it should emphasize the development of FP and LP, respectively. Then the corresponding service system needs to be established. Further, the technical and scientific education of the personnel needs to be upgraded and improved. Therefore investment research with the aim of realizing scientific management and production should be discussed in the

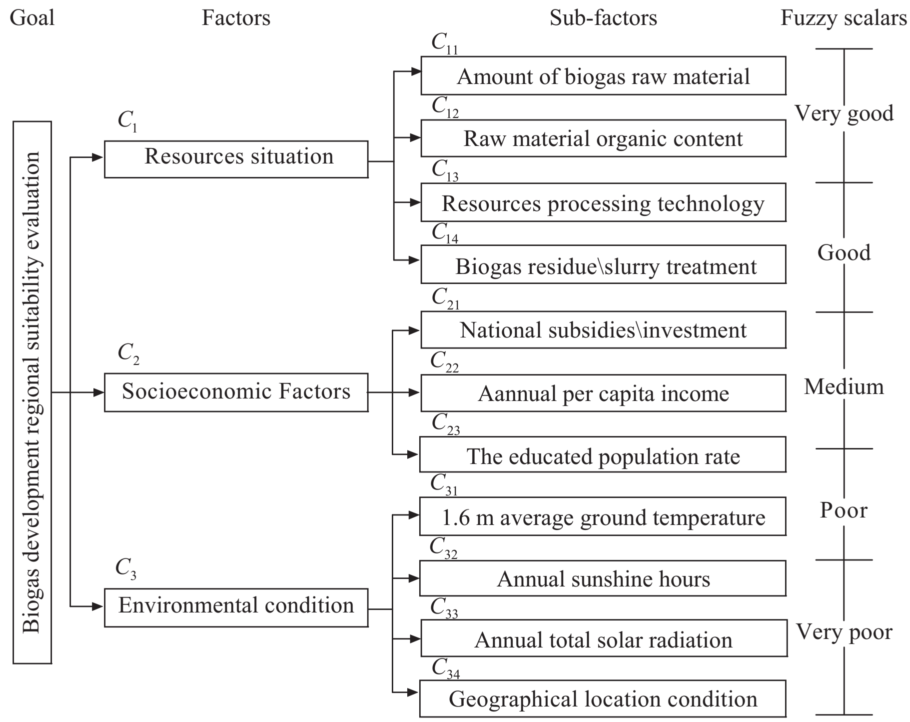

Fig. 3. AHP model for the regional suitability evaluation of biogas applications.

Table 6
The factors fuzzy pair-wise comparison matrix.

Factors	C_1	C_2	C_3
C_1	(1, 1, 1)	(1, 3/2, 2)	(3/2, 2, 5/2)
	(1, 1, 1)	(2/5, 1/2, 2/3)	(1, 3/2, 2)
	(1, 1, 1)	(1, 3/2, 2)	(2, 5/2, 3)
	…	…	…
C_2	(1/2, 2/3, 1)	(1, 1, 1)	(2/3, 1, 2)
	(1/2, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
	(2/5, 1/2, 2/3)	(1, 1, 1)	(3/2, 2, 5/2)
	…	…	…
C_3	(2/5, 1/2, 2/3)	(1/3, 2/5, 1/2)	(1, 1, 1)
	(1/2, 2/3, 1)	(2/3, 1, 2)	(1, 1, 1)
	(1/2, 1, 3/2)	(1/2, 2/3, 1/2)	(1, 1, 1)
	…	…	…

Table 7
The factors mean values of fuzzy comparison.

Factors	C_1	C_2	C_3
C_1	(1.000, 1.000, 1.000)	(0.712, 0.923, 1.238)	(0.836, 1.124, 1.427)
C_2	(0.684, 0.887, 1.192)	(1.000, 1.000, 1.000)	(0.798, 1.038, 1.352)
C_3	(0.735, 0.963, 1.264)	(0.751, 0.986, 1.289)	(1.000, 1.000, 1.000)

further research. Preliminary regional division of the development of biogas plants nationwide can also be determined by the expert team based on the proposed model. The model shows that the FP is the preferred biogas application for the rural areas and less well-off places in southern China, and should also be the state-supported FP construction region. Small towns that cannot be covered by the urban sewage networks are the most suitable construction areas for the MP. The preferred construction regions for the LP are the east coast developed regions and the inland cities' suburbs, among which grain producing areas are the priority.

Table 8
Computed global weights for sub-factors.

Sub-factor	Main factor and local weights			Global weights
	C_1 (0.345)	C_2 (0.326)	C_3 (0.329)	
C_{11}	0.4571			0.1577
C_{12}	0.2726			0.0940
C_{13}	0.1542			0.0532
C_{14}	0.1171			0.0404
C_{21}		0.2563		0.0835
C_{22}		0.4172		0.1360
C_{23}		0.3275		0.1067
C_{31}			0.3152	0.1037
C_{32}			0.2534	0.0833
C_{33}			0.2143	0.0705
C_{34}			0.2181	0.0717

5. Conclusion

In this paper, the current status and the characteristics of biogas applications in China was discussed. The characteristics of three major kinds of biogas plants were introduced. Finally, a suitability evaluation based on regional and biogas plant characteristics was analyzed using a fuzzy-AHP model. The results show that biogas construction depends significantly on regional characteristics and it illustrates that the proposed model could effectively provide decision support for development strategies concerning regional development of biogas plants and for the adjustment of the scale of biogas development to match local requirements. A great deal of work needs to be done to modernize and develop the different biogas plants and promote the formation of a biogas-centric industrial chain (biogas production, power generation, heating, biogas comprehensive utilization). The

Table 9
Total evaluation for the three biogas applications in Sichuan and Shandong.

Region	FP			MP			LP		
	GW	FLV	GW × FLV	GW	FLV	GW × FLV	GW	FLV	GW × FLV
Sichuan	0.1677	1	0.1677	0.1577	0.5	0.0789	0.1577	0.5	0.0789
	0.1440	0.75	0.1080	0.0979	0.5	0.0490	0.0940	0.5	0.0470
	0.0632	0.75	0.0474	0.0835	0.25	0.0209	0.0649	0.25	0.0162
	0.0404	0.75	0.0303	0.0497	0.25	0.0124	0.0677	0	0.0000
	0.0735	1	0.0735	0.0835	0.5	0.0418	0.0835	0.25	0.0209
	0.0960	0.5	0.0480	0.141	0.5	0.0705	0.1579	0.5	0.0790
	0.0867	0.25	0.0217	0.1152	0.25	0.0288	0.1473	0.25	0.0368
	0.1037	0.75	0.0778	0.0842	0.75	0.0632	0.0749	0.75	0.0562
	0.0833	0.25	0.0208	0.0745	0.25	0.0186	0.0680	0.25	0.0170
	0.0705	0.5	0.0353	0.0629	0.5	0.0315	0.0527	0.5	0.0264
	0.0710	0.5	0.0355	0.0499	0.5	0.0250	0.0314	0.5	0.0157
RSD			0.6659			0.4403			0.3940
Shandong	0.1677	0.25	0.0419	0.1577	0.75	0.1183	0.1577	0.75	0.1183
	0.1440	0.25	0.0360	0.0979	0.5	0.0490	0.0940	0.75	0.0705
	0.0632	0.5	0.0316	0.0835	0.5	0.0418	0.0649	1	0.0649
	0.0404	0.5	0.0202	0.0497	0.75	0.0373	0.0677	0.5	0.0339
	0.0735	0.25	0.0184	0.0835	0.5	0.0418	0.0835	0.75	0.0626
	0.0960	0.5	0.0480	0.141	0.75	0.1058	0.1579	1	0.1579
	0.0867	0.5	0.0434	0.1152	0.5	0.0576	0.1473	0.75	0.1105
	0.1037	0.5	0.0519	0.0842	0.5	0.0421	0.0749	0.5	0.0375
	0.0833	0.75	0.0625	0.0745	0.75	0.0559	0.0680	0.75	0.0510
	0.0705	0.5	0.0353	0.0629	0.75	0.0472	0.0527	0.75	0.0395
	0.0710	0.25	0.0178	0.0499	0.5	0.0250	0.0314	0.75	0.0236
RSD			0.4068			0.6223			0.7701

findings can also aid further research on balancing energy supply and demand, energy policy formation, and the regional eco-environment development in China. This paper presented a decision support model for the regional suitability of biogas plants. The detailed regional division for nationwide development planning of biogas plants will be discussed in our future work.

Acknowledgments

This research is supported by the Major Bidding Program of National Social Science Foundation of China (Grant no. 12&ZD217). The authors would like to thank the anonymous referees for their insightful comments and suggestions to improve this paper, as well as Low Carbon Technology and Economy Research Center of Sichuan University for helpful comments and discussion.

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